Kinematically complete study of the ^{7}Li$(p,\gamma)^8$Be$^* \rightarrow 2\alpha$ reaction at $E_p = 25$ MeV

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A kinematically complete study of the ^{7}Li$(p,\gamma)^8$Be$^* \rightarrow 2\alpha$ reaction at $E_p = 25$ MeV is described. An upper limit of $d\sigma/d\Omega < 0.04$ μb sr^{-1} is reported for the $\theta_\gamma = 90°$ capture cross section to the 2^+ states at 16.62 and 16.93 MeV, which is five times smaller than published results. This new datum is shown to be more consistent with a semidirect reaction mechanism involving the giant dipole resonance built on the ^{8}Be* 2.94-MeV state than the previously proposed direct reaction mechanism.

Radiative proton capture leading to highly excited states has only been investigated for a few favorable light-nucleus systems.[1–7] This is mainly due to the difficulties experienced in obtaining gamma spectra in regions well below the ground-state capture peaks. At these E_γ energies, the spectra are frequently affected by γ rays from other reactions, capture γ rays on target contaminants, or residual pulse pileup. The few measurements that have been achieved do, however, show that capture to highly excited states is an important reaction channel with typical cross sections 5–10 times larger than those for ground-state capture.

In all cases the states most strongly populated have fairly simple 1p-1h structures. Also, the (p,γ) reaction in these light nuclei appears to be dominated by a direct reaction mechanism (DRM) and a semidirect process in which the giant dipole resonance (GDR) built on each excited (Brink hypothesis[8]) acts as a doorway state. Various estimates of these processes are discussed in Refs. 1–5 and 9.

A study of the ^{7}Li$(p,\gamma)^8$Be* reaction leading to the $J^\pi = 2^+$ isospin mixed doublet (IMD) at $E_x = 16.63$ and 16.92 MeV (Ref. 1) suggests that the DRM is dominant for this reaction channel. Measurements were made at low bombarding energies by detecting the correlated pairs of α particles emitted in the decay of the IMD and at higher energies by detecting the γ rays feeding these levels. These results show that the cross section peaks at $E_p \sim 9$ MeV, which was considered to be too low in energy to be consistent with a GDR mechanism (typical GDR excitation energies for light nuclei are $\hbar\omega \sim 25$ MeV). All the data up to 30 MeV were, however, reasonably well described by a DRM calculation.[1]

In this Brief Report we report on a triple-coincidence $(\gamma + 2\alpha)$ kinematically complete measurement of the ^{7}Li$(p,\gamma)^8$Be* cross section at $E_p = 25$ MeV, the results of which contradict the conclusions of Ref. 1. The main advantage of our measurement compared to the previous experiment[1] is that spurious results arising from γ-ray spectrum corruption were eliminated by making use of the fact that the ^{7}Li$(p,\gamma 2\alpha)$ reaction has the largest Q value (17.25 MeV) of any of the expected reactions, including those due to contaminants. Furthermore, it was possible to determine the ^{8}Be* excitation energy more accurately because E_x could be deduced from the decay α-particle energies measured using silicon strip detectors.

The measurement was made at the SERC Nuclear Structure Facility, Daresbury, United Kingdom. A 3–6-nA beam of 25-MeV protons was directed onto a 400-μg cm^{-2} ^{7}LiF target supported on a 25 μg cm^{-2} C backing. The target was orientated with its plane at 25° to the beam direction so as to maximize the thickness presented to the beam and minimize the thickness through which particles traveled to the detectors. The beam was stopped and current integrated in a Faraday cup $\sim$8 m downstream from the target.

Particles were detected in two large-area 50×50-mm^2 silicon strip detectors, positioned 2 cm above and below the beam axis. Each detector was divided into ten equal strips separated by 100 μm. The angular ranges of the upper and lower detectors were 45°–120° and 22°–90°, respectively, these ranges being chosen to maximize the coincidence efficiency for detecting pairs of α particles from ^{8}Be* decays in the range $E_x = 10-30$ MeV and to minimize the energy losses in the target. The efficiency for detecting the coincidence α particles from ^{8}Be* decays, with the assumption of isotropic emissions in the center of mass, was determined by a Monte Carlo calculation to be $\sim$38%. Each strip detector was accurately calibrated using a ^{228}Th α source and a precision pulse generator. A typical counting rate of pulses above a 2-MeV threshold was $\sim 5 \times 10^3$ Hz per detector strip.

Gamma rays were detected by a 25×35-cm^2 NaI(Tl) detector positioned 48 cm from the target in the 90° direction. The detector was shielded from beam-associated γ rays and neutrons by layers of polyethylene (20 cm thick), Li_2CO_3+paraffin (10 cm), Flexiboron (0.5 cm), and Pb (7.5 cm), except for the front face where only the Li_2CO_3+paraffin and Flexiboron layers were used. The gamma-ray attenuation through the chamber wall and shielding was measured to be 34% at 1.33 MeV, which translates to $\sim$20% at $E_\gamma = 20$ MeV. The Na(Tl) detector was calibrated using standard γ sources and the ^{127}I n-capture peak at 6.8 MeV.

Double-coincidence (x_1,x_2), (x_1,γ), and (x_2,γ) events, and triple-coincidence (x_1,x_2,γ) events were recorded using conventional electronics which included pileup rejection. The time resolution for the particle-

particle coincidences was ~ 2 ns full width at half maximum (FWHM) and for the particle-gamma coincidences ~ 5 ns, which allowed neutrons detected in the NaI(Tl) detector to be eliminated by the time-of-flight method. The particle-particle double-coincidence events were prescaled by a factor of 200 or more to reduce the event-taking rate to a manageable level.

Figure 1(a) shows a gamma-ray spectrum in coincidence with the upper particle detector. All the peaks below 7 MeV have been identified with reactions on the ^{19}F and ^{12}C present in the target. These data provide a valuable check on the calibration and show that the online γ-energy resolution was good (FWHM 150 keV at 4.4 MeV). The arrow marks the expected position for a γ peak from the reaction ^{7}Li$(p,\gamma)^8$Be* leading to the IMD.

A typical summed-energy particle-particle coincidence spectrum is shown in Fig. 1(b). A crude selection procedure has been applied to remove coincidence events where the particles are not sufficiently well correlated in angle to have arisen from the $^8\text{Be}^* \rightarrow \alpha_1 + \alpha_2$ decays. The sharp peak observed at 42.25 MeV is due to the reaction ^{7}Li$(p,2\alpha)$. The data in the range $E = 10-25$ MeV mostly correspond to the transmission of $z=1$ particles through the detectors. However, there is an indication of a possible peak at 22 MeV, which could be due to the decay $\alpha^* \rightarrow t + p$ following the reaction ^{7}Li$(p,\alpha\alpha^*)$. Confirmation of this interpretation was obtained by selecting events in which one strip in one detector gave a signal in coincidence with signals from two strips in the other detector. The result is shown in the inset of Fig. 1(b). These data establish that the detectors were accurately calibrated and that the resolution at 42 MeV was ~ 500 keV FWHM.

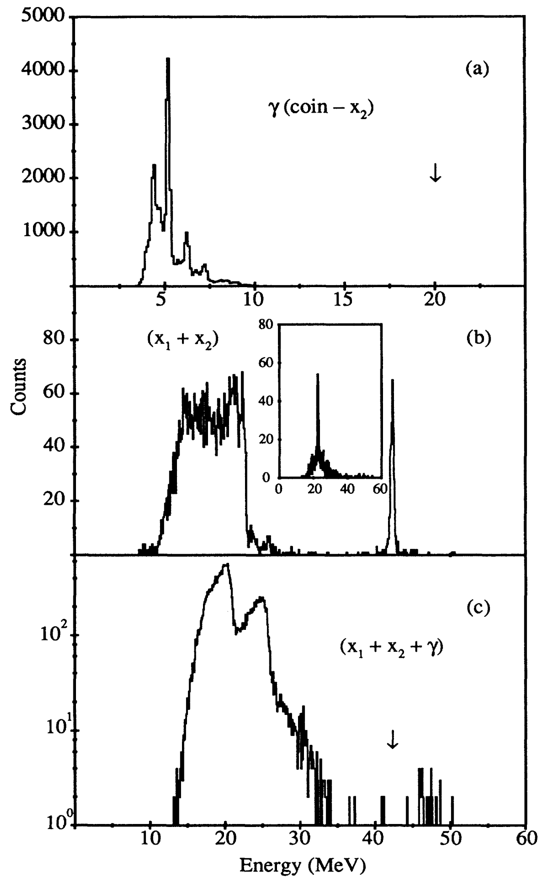

FIG. 1. (a) Typical γ-ray spectrum in coincidence with the upper particle detector. The arrow marks the expected position of the coincident γ peak from IMD excitation. (b) Summed-energy spectrum for x_1 and x_2 particle coincidences. Inset: Data corresponding to two signals present in one of the detectors. (c) Summed-energy spectrum from triple-coincidence $x_1+x_2+\gamma$ events. The arrow marks the expected position of the kinematically complete summed peak.

Figure 1(c) shows an example of the summed-energy particle-particle-gamma triple-coincidence spectra obtained. The crude selection procedure described earlier has again been applied. The most significant feature of this spectrum is the absence of events in the region where kinematically complete detections of two α particles and a γ ray following the reaction ^{7}Li(p,γ)Be*$\rightarrow 2\alpha$ would be expected to give data. Events above 45 MeV correspond to low-energy γ rays randomly summing with $\alpha_1+\alpha_2$ pulses from the 42.25-MeV peak (random coincidences have not been subtracted). A consideration of all the data taken with an assumed peak to total efficiency of 85% for the NaI(Tl) detector gave an upper limit (two standard deviations confidence level) to the 90° cross section for the ^{7}Li$(p,\gamma)^8$Be* reaction leading to α-decaying highly excited states ($E_x \geq 10$ MeV) of $d\sigma/d\Omega < 0.04$ μb sr^{-1}.

The upper limit given here for the ^{7}Li$(p,\gamma)^8$Be* cross section at $E_p = 25$ MeV is approximately 5 times smaller than the result presented previously for the reaction leading to the IMD states at $E_x = 16.63$ and 16.92 MeV.[1] A most likely explanation of the difference is that the previous results which were based on a single-arm γ measurement are corrupted by gamma rays from other reactions in the target. The γ spectrum shown at $E_p = 13$ MeV in Ref. 1 has other unidentified peaks in the neighborhood of the peak of interest. Possible candidates for the contaminant reactions are ^{6}Li$(p,\gamma)^7$Be, ^{12}C$(p,\gamma)^{13}$N, ^{16}O$(p,\gamma)^{17}$F, and ^{14}N$(p,\gamma)^{15}$O, which have ground-state Q values of 5.61, 1.94, 2.35, and 7.44, respectively. These are higher than those for the ^{7}Li$(p,\gamma)^8$Be* reaction populating the IMD states, which are $Q = 0.62$ and 0.33 MeV, respectively. Taking into account the different kinematics involved, γ peaks from the reactions on the impurities leading to low-lying excited states would at certain higher bombarding energies be under the γ peak of interest. Also, at these energies, the γ resolution would be insufficient to properly resolve the peaks and residual pileup could be important. These effects would, therefore, lead to an overestimate of the cross section, particularly at the higher energies. Some support for these suggestions come from Ref. 1 where it is stated that the cross section could not be obtained from γ measurements below $E_p = 11.5$ MeV and in the regions of 15 and 18 MeV because of contamination of the spectra, particularly from the ^{12}C$(p,p'\gamma)$ reaction.

Figure 2 shows the result presented here compared to

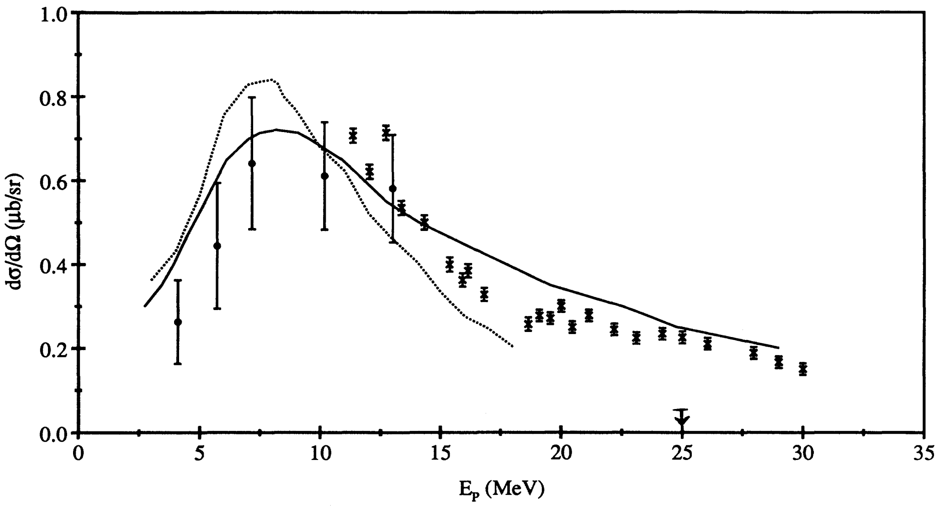

FIG. 2. Excitation function results for the ^{7}Li(p,γ)Be* reaction leading to the IMD. The crosses and solid circles are data from Ref. 1 obtained from γ measurements and 2α coincidence measurements, respectively. The datum at $E_p = 25$ MeV is the cross-section limit present here. The solid curve is the result of a DRM calculation (Ref. 1). The dotted curve is the ^{7}Li(p,γ_1)Be* data of Ref. 10, normalized to the data of Ref. 1 below $E_p = 17.5$ MeV (see text).

the data of Ref. 1 and the DRM calculation. This new result suggests that the data of Ref. 1 are in error above $E_p \sim 20$ MeV and, in addition, removes the unaccounted for change in slope of the data at this energy. Clearly, a different interpretation of the data is also indicated since the new point shows a much more rapid falloff of the excitation function than given by the DRM calculation (solid line). Furthermore, it opens up the interesting question of whether a GDR mechanism might be more appropriate to describe the rapid fall in the cross section above $E_p \sim 9$ MeV.

To consider this we compared the data to the results of a similar ^{7}Li(p,γ)^{8}Be* experiment leading to the 2^+ first excited state $E_x = 2.94$ MeV.[10] The dotted curve in Fig. 2 shows a fit to the result of this experiment[10] scaled down in magnitude such that the integrated cross section up to 17.5 MeV agrees with that for the IMD data of Ref. 1. Interestingly, it can be seen that the IMD excitation function peaks at a similar energy to the 2^+ excited-state excitation function and falls off at a similar rate. This suggests that the feeding of the IMD 2^+ states and the $E_x = 2.94$ MeV 2^+ state could have similar origins.

The reaction leading to the 2^+ first excited state at 2.94 MeV is interpreted[10] as proceeding through an $E_x = 23.8$ MeV GDR state built on the 2.94-MeV state according to the Brink hypothesis. This was deduced from the result that the ^{7}Li(p,γ) excitation function peaks 2.2 MeV higher than ^{7}Li(p,γ_0) which is an increase approximately equal to the energy of the state (2.94 MeV). Also, the integrated yields are in the expected ratio deduced from a GDR model and the γ-ray angular distributions are all consistent with predominantly $E1$ γ emission.[10] Our result would suggest that the ^{7}Li(p,γ)^{8}Be* reaction leading to the $J^\pi = 2^+$ IMD states also proceeds through the 23.8-MeV GDR. This possibility is not unexpected because any GDR state can have widths associated with γ decay to other low-lying states. Such an explanation merely corresponds to an extension of the Brink hypothesis to allow for a giant dipole resonance built on a state other than the one being considered to act as a doorway state.

A comparison of the 90° yields from Refs. 1 and 10 would suggest a result $R \sim 0.1$ for the γ branching ratio ($E_x = 23.8$ MeV GDR$\rightarrow$IMD states)/($E_x = 23.8$ MeV GDR$\rightarrow$2.94 MeV level). As an initial guide to a possible interpretation of this result is interesting to consider the results of measurements on the ^{27}Al(p,γ)^{28}Si* (Ref. 5) and ^{39}K(p,γ)^{40}Ca* (Ref. 6) reactions. From the interpretation of these results, it was found that feeding to different states in the final channel was strongly influenced by the corresponding spectroscopic factors for single-particle transfer. The results of the present experiment are also likely to be influenced by the spectroscopic factors, even though the interpretation with regard to the GDR states involved is different. Following this line of argument, we note that the ratios of calculated single-particle transfer spectroscopic factors for the IMD 2^+ states to the 2.94-MeV 2^+ state are $R \sim 1$.[11] Even though the exact nature of the GDR excitation is uncertain, such a large spectroscopic ratio would be at least be consistent with considerable feeding to the IMD states.

Unfortunately, the experimental situation with regard to the p-transfer reaction is not sufficiently clear to allow a check on the calculations. The ^{7}Li(d,n)Be* reaction is known to strongly excite the 2.94-MeV and IMD states.[12,13] However, the relative yields could not be obtained because the angular correlations of the n and 2α particles in the final state were not sufficiently well determined.[13] The ^{7}Li(^{3}He,d)^{8}Be*$\rightarrow 2\alpha$ reaction appears to proceed almost entirely through the IMD,[12,14] with only a small cross section for the reaction through the 2.94-MeV state, although quantitative relative strengths are not reported. Clearly, more work is required to determine the proton spectroscopic factors. The results as they stand at present do not, however, contradict an explanation of the ^{7}Li(p,γ)^{2}Be* (IMD) reaction in terms of it proceeding through the GDR built on the low-lying 2.94-MeV 2^{+} state, the relatively large cross section being a consequence of a large spectroscopic factor for proton transfer to the IMD states. Thus we conclude that the reaction mechanism proposed here could explain the results for the ^{7}Li(p,γ)^{8}Be* reaction leading to the 16.62- and 16.93-MeV IMD states.

[1]S. Manglos, N. R. Robertson, H. R. Weller, and D. R. Tilley, Phys. Rev. C **24**, 2378 (1981).

[2]M. A. Kovash *et al.*, Phys. Rev. Lett. **42**, 700 (1979).

[3]H. R. Weller *et al.*, Phys. Rev. C **25**, 2921 (1982).

[4]M. Anghinolfi, Nucl. Phys. **A399**, 66 (1983).

[5]D. H. Dowell *et al.*, Phys. Rev. Lett. **50**, 1191 (1983).

[6]D. H. Dowell, in *Capture Gamma-Ray Spectroscopy and Related Topics (Holiday Inn—World's Fair, Knoxville, Tennessee)*, Proceedings of the Fifth International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics, AIP Conf. Proc. No. 125, edited by S. Raman (AIP, New York, 1984).

[7]K. A. Snover, Annu. Rev. Nucl. Part. Sci. **36**, 545 (1986).

[8]D. M. Brink, Ph.D. thesis, University of Oxford, 1955.

[9]L. G. Arnold, Phys. Rev. Lett. **42**, 1253 (1979).

[10]G. A. Fisher, P. Paul, F. Riess, and S. S. Hanna, Phys. Rev. C **14**, 28 (1976).

[11]S. Cohen and D. Kurath, Nucl. Phys. **A10**, 1 (1967).

[12]F. Ajzenberg-Selov, Nucl. Phys. **A490**, 1 (1988).

[13]R. E. Warner *et al.*, Nucl. Phys. **A470**, 339 (1987).

[14]V. Volkovic *et al.*, Nucl. Phys. **A96**, 241 (1967).